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Diagnostic Tools for Integrated In Situ Air Sparging Pilot Tests

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Pilot tests are an important tool for improving our conceptual understanding of in situ air sparging (IAS) behavior at a site. Unfortunately, prediction of long term performance based on pilot tests has proved to be difficult (Johnson, et al., 1997). Nevertheless pilot tests have proven useful as a means of identifying "red flags" prior to installation of full-scale systems. In that context, IAS pilot tests are most useful when designed to: a) look for indicators of infeasibility, b) characterize the air distribution to the extent practicable, and c) identify any safety hazards to be addresses in the full-scale design. Prior to conducting the pilot test activities outlined in the paper the following tasks should be completed (J.P. Johnson et al., 2000):

1. Define the target treatment zone
2. Propose a conceptual model for the air distribution in the treatment zone
3. Determine if 15 ft well spacings are cost prohibitive, and if so, determine the minimum injection well spacing that is not cost prohibitive.
4. Propose the depth, location, and construction specifics of a pilot test well.
5. Determine the expected range of operating pressures for the injection well.

If based on the previous site activities IAS is chosen as the remediation technology for the site, it is recommended that the series of pilot test activities described in the report be conducted. If in the preliminary assessment it was determined that the well spacings of 15 feet are cost effective, the first six activities described in the report should be conducted. If a greater well spacing is required, additional site-specific activities should be conducted. These are also described in the report.

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Diagnostic Tools for Integrated In Situ Air Sparging Pilot Tests

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1.0 INTRODUCTION

Pilot tests are an important tool for improving our conceptual understanding of in situ air sparging (IAS) behavior at a site. Unfortunately, prediction of long-term performance based on pilot tests has proved to be difficult (Johnson et al., 1997). Nevertheless, pilot tests have proven useful as a means of identifying "red flags" prior to installation of full-scale systems. In that context, IAS pilot tests are most useful when designed to: a) look for indicators of infeasibility, b) characterize the air distribution to the extent practicable, and c) identify any safety hazards to be addressed in the full-scale design.

Prior to conducting the pilot test activities outlined in the following sections, the following tasks should be completed (P.C. Johnson et al., 2000):

a) Define the target treatment zone (i.e., the depth interval and area which is to be treated by the IAS system).

b) Propose a conceptual model for the air distribution in the treatment zone (e.g., based on site information determine if the aquifer is homogeneous or stratified).

c) Determine if 15-ft well spacings are cost-prohibitive, and if so, determine the minimum injection well spacing that is not cost-prohibitive.

d) Propose the depth, location, and construction specifics of a pilot test well.

e) Determine the expected range of operating pressures for the injection well.

If, based on previous site activities IAS is chosen as the remediation technology for the site, it is recommended that the series of pilot test activities summarized in Table 1 (and discussed below) be conducted. If in the preliminary assessment it was determined that well spacings of 15 ft are cost effective, the first six activities in Table 1 (PT1 through PT6) should be conducted (Standard Pilot Test Approach). If a greater well spacing is required, additional site-specific activities should be conducted. These include the sulfur hexafluoride (SF_6)-distribution test (PT7) and possibly geophysical tests (PT8) to define the zone of aeration (Site-Specific Pilot Test Approach). In deciding whether or not to perform the additional SF_6-distribution and geophysical tests, the cost of the additional tests, the potential cost-savings of larger injection well-spacings, the impact of larger or smaller well-spacings on remediation performance, and the benefits of better understanding the air distribution should all be considered.

2.0 PILOT TEST EQUIPMENT

The following equipment is needed to conduct the pilot test activities: a) at least one air injection well equipped with a well-head pressure gauge, flowmeter, and valve; b) an air supply compressor; c) one to three groundwater piezometers or monitoring wells; and d) several groundwater and vadose zone monitoring points. In addition, a vapor extraction system may be needed to reduce the potential for adverse vapor migration impacts (or it may be required by regulation).

The air injection well should be similar to that envisioned for full-scale implementation. A typical air injection well is a 1- to 4-inch-diameter vertical well having 1 to 5 ft-long screened interval installed from 1 to 5 ft below the target treatment zone. Five feet below the target treatment zone is prefaerable; however, at some sites, 5 ft is not available due to site stratigraphy and less than 5 ft will likely be acceptable. Most screened intervals are generally not placed deeper than 10 ft below the treatment zone as the risk of the air not reaching the target treatment zone increases with increasing separation. It is important to ensure a good annular air flow seal between the top of the screened interval and the water table.

The air injection compressor should be capable of providing at least 20 ft^3/min at pressures of up to 10 to 15 psig above the calculated hydrostatic pressure (see PT2 below). Additional description for sizing a compressor is provided in Section 3.2.

To the extent possible, existing groundwater monitoring wells and other monitoring installations should be incorporated into the pilot test design. A typical pilot test monitoring network consists of a) one to three groundwater piezometers or monitoring wells equipped with water-level pressure transducers, b) six or more groundwater sampling points, and c) six or more vadose zone sampling points. The piezometers and groundwater sampling points ideally should be screened only within the target treatment zone. Vadose zone sampling points should be screened over a narrow interval (1 to 2 ft maximum) and placed just above the capillary fringe. For shallow sites (<30 ft to groundwater), monitoring networks like these are often quickly and cost-effectively installed with direct-push methods. Small diameter (¼- to 3/8-inch) discrete (6- to 20-inch length) direct push implants are good candidates for the groundwater and vadose zone monitoring points. At deeper sites, or sites with access restrictions, practical considerations may dictate the use of fewer wells, multi-level samplers, and a heavier reliance on existing groundwater monitoring wells having screens that extend above the water table (these can be used to house pressure transducers and to collect groundwater and vapor samples).

A sample pilot test layout is shown in Figure 1. In choosing the monitoring lay-out, it is important to recognize that air distributions often have unpredictable preferred directions, and therefore a spatially-distributed monitoring network is preferred over installations having monitoring points emanating out from the injection well in a line in one or two directions. Furthermore, the locations should reflect the hydrogeologic setting and the tentative well spacings as described in item (c) above. In near homogeneous settings, the monitoring network need not extend more than 20 ft out from the injection well. In cases where close well-spacings are prohibitive, the monitoring network should extend out at least a distance equal to one-half to three-fourths of the minimum non-cost-prohibitive well-spacing distance.

3.0 PILOT TEST ACTIVITIES

In most cases, the events outlined in Table 1 should be conducted in the sequence presented. In this section each of the activities will be discussed in greater detail. In a number of cases a detailed protocol for the activities has been published and are cited when appropriate. The task-by-task discussion will be followed by a case history in which the various pieces of the pilot test are combined to interpret what is occurring at the site and assess if IAS is appropriate at the site.

3.1 Baseline Sampling (PT1)

Baseline sampling represents a critical step in the pilot test process. For several of the parameters, it is important to collect data prior to any IAS activity to ensure that initial conditions are understood. In particular, those parameters include dissolved oxygen (DO) concentrations and any geophysical measurements (if geophysical tests are to be conducted as part of the pilot test). It is also important to collect baseline pressure transducer data with a data-logger. The pressure data should be collected for a sufficiently long period to assess diurnal changes in water level (e.g., tidal fluctuations) if they are believed to be a significant.

If a soil vapor extraction (SVE) system is to be used in conjunction with the IAS system, then the SVE system should be operated for a period of time prior to IAS startup primarily to ensure that the SVE system is operating properly to capture the initial high mass loading from air sparging. During this period, it may also be of interest to monitor SVE off-gas for the contaminants of interest in order to establish mass loading from volatilization from the vadose zone compared to volatilization from groundwater. Ideally, prior to initiating IAS, the off-gas concentrations should have stabilized to the extent that changes in off-gas concentrations due to IAS operation can be easily determined. In many cases it may be sufficient to monitor those off-gas concentrations with a hand-held field instrument, rather than requiring more sophisticated chromatographic analysis. If off-gas is regulated, regulatory requirements often will dictate which analytical method must be used.

If an SVE system is not part of the IAS system, then soil gas concentrations (including both contaminant and oxygen concentrations) should be measured prior to IAS startup. The initial contaminant concentration in the vadose zone can be used to calculate roughly contaminant mass removal from groundwater via volatilization (see Section 3.5). Initial oxygen concentrations are useful for measuring bioactivity in the vadose zone. Hand-held instruments should be appropriate for this since soil gas concentrations of contaminants are rarely regulated.

3.2 Air Injection Flow Rate and Injection Pressure (PT2)

Prior to pilot test activities, it is important to evaluate the expected operating pressure for the IAS system. This is important both for the selection of the correct air injection system and for the prevention of pneumatic fracturing of the aquifer. Outlined below is the general procedure for estimating the minimum pressure required to initiate sparging and the maximum pressures that should be exerted on the aquifer.

The operating pressure for an IAS system will be determined by the depth of the IAS well below the water table and the permeability of the aquifer. The minimum injection pressure necessary to induce flow (P_{min} [psig]) is given by:

$$P_{min}\,(\text{psig}) = 0.43\ H_h + P_{packing} + P_{formation} \tag{1}$$

The pressure at which fracturing of the aquifer can occur is given by:

$$P_{fracture}\,(\text{psig}) = 0.73\ D \tag{2}$$

Where H_h = depth below the water table to the top of the injection well screened section (e.g., the hydrostatic head) (ft); $P_{packing}$ and $P_{formation}$ = air entry pressures for the well annulus packing material and the formation (psig); and D = depth below ground surface to the top of the air injection well screened interval (ft).

For typical IAS wells and applications, $P_{packing}$ and $P_{formation}$ are small compared to the contribution from the hydrostatic head (air entry pressures are generally <0.2 psig for sands, <0.4 psig for silts, but may be >1.5 psig in some clayey settings). At start-up, it is not unusual for users to exceed P_{min} by as much as 5 to 10 psig to initiate flow quickly. The injection pressure then generally declines to about P_{min} as steady flow conditions are approached. Pressures in excess of $P_{fracture}$ can cause fracturing of the formation; however, as the pressure drops off rapidly away from an injection point, the extent of fracturing in most cases is expected to be limited to the area immediately surrounding the well.

In general, it is recommended that oil-less compressors be used for the pilot test (even if it is not chosen for operation of the full IAS system), because it eliminates uncertainties relating to air flow rate and potential overheating. However, other pumps may be used for air injection, but the practitioner may experience more operational difficulties, depending on site conditions.

As part of the initial shakedown of the IAS system, the air injection system must be tested. During this process, it is important to measure both the air flow rate and the injection pressure to ensure that neither P_{min} or $P_{fracture}$ are exceeded at the required air flowrate. There are two general approaches for the initial introduction of air into the subsurface. The first is to include a "vent valve" in the injection air line. This valve should be fully open to begin the test and then be closed slowly while monitoring the increase in pressure and flowrate up to the desired flowrate. During this process, care should be taken not to exceed the upper pressure limit for the system (as determined by the calculations described above). In addition, if the air injection system requires some minimum airflow to provide cooling for the motor/pump, total air flow and system temperature should also be monitored.

A second approach for IAS startup is to determine the maximum pressure for air injection and to include an in-line pressure regulator in the air injection line. (This approach is best suited to oil-less compressors that do not require airflow for cooling.) In this case, the pressure can be set at the IAS well head and flow allowed to increase as air pathways in the aquifer become developed. In general, when using this approach it will be necessary to make adjustments in the system to achieve the desired flow rate.

Based on the design paradigm of Johnson et al. (2000) it is desirable to begin the test with an air injection flow rate of 20 ft^3/min if possible. The air injection pressure at the on-set of flow should be recorded, as well as pressures every 5 to 10 minutes until the pressure and flow stabilize.

3.3 Groundwater Pressure Measurements During IAS Startup and Shutdown (PT3)

Once the flow and pressure conditions for sparging have been established (PT2), groundwater pressures during IAS startup and shutdown can be determined. The primary objective of this test is to assess the time required for airflow distribution to come to steady state. As discussed by Johnson et al. (2000a), pressure measurements provide an easy and sensitive means of assessing if IAS air is stratigraphically trapped below the water table. The pressure measurements can also provide a measure of site permeability, based on the magnitude of the response. In general terms, during IAS startup groundwater pressures will increase because air is being pushed into the formation faster than the water can move away from the IAS well. Typically, as long as the volume of air below the water table is increasing, the groundwater pressure will remain above pre-IAS levels. As a result, the time required for groundwater pressure to return to pre-IAS values is a good measure of the time required for the macro-scale air distribution to come to steady state. For media which are relatively homogeneous with respect to air flow (e.g., uniform sands), the time required for IAS pressures to return to pre-IAS values will generally be measured in tens of minutes to a few hours. If the site is stratified with lower-permeability layers, then the groundwater pressure may remain elevated for tens of hours to days.

The magnitude of the groundwater pressure response can be from millimeters to a few meters of water. In general, if the injection rate is on the order of 20 ft^3/min and the response is on the order of millimeters, the medium is very coarse (e.g., gravels). Pressure responses in sands are typically on the order of tens of centimeters and responses of a meter or more may occur in finer-grained media or in media where the air is stratigraphically confined.

Generally, at sites where groundwater pressures remain elevated by more than a few tens of centimeters for more than 8 hours, it can be assumed that the air distribution is controlled to a high degree by the structure of the aquifer, and it will be important to determine if the air is being delivered to the treatment zone in an effective manner.

3.4 Helium Distribution and Recovery Test (PT4)

Helium can be used in two primary ways as a tracer for IAS systems (Johnson et al., 1996; Johnson et al., 2000b). The first of those is to identify the locations at which IAS air moves from the groundwater zone to the unsaturated zone. The second, if an SVE system is present, is to assess the effectiveness with which the SVE system is capturing the IAS air.

To conduct the first test (in the absence of an SVE system), helium is added to the IAS air at a known rate to achieve a steady helium concentration of about 2 to 10% v/v. Immediately upon initiating helium injection, all of the vadose zone monitoring points and groundwater monitoring wells (if screened above the water table) should be monitored for helium. Sampling should continue and be repeated at monitoring points and wells up until 20 minutes after initiation of helium injection. After this time period, helium is likely to be well mixed in the subsurface and appearance at monitoring points will no longer be representative of the point where helium entered the vadose zone from the saturated zone.

To conduct the second test (if an SVE system is operating), helium should be injected into the IAS air at a known rate and the off-gas be monitored for the appearance of helium. Injection should continue until a stable helium concentration is achieved. If the helium injection rate, air injection rate, and SVE extraction rate are all known, then the fraction of the helium recovered by the SVE system can be calculated simply as the ratio:

$$\text{Percent helium recovered} = \frac{\text{Observed helium concentration (\%)}}{\dfrac{\text{Helium injection rate}}{\text{Air extraction rate}}} \tag{3}$$

As discussed in Johnson et al. (2000b), this equation assumes that the air extraction rate exceeds the IAS air injection rate. Helium recovery data tends to fall into two ranges. The IAS air either makes it to the vadose zone and is collected by the SVE system resulting in a high (e.g., >70%) recovery, or the air is stratigraphically trapped, pushing it beyond the SVE system or out of monitoring wells, in which case the recovery is low (e.g., <20%).

3.5 Soil Gas Monitoring (PT5)

In the absence of an SVE system, soil gas samples should be collected for contaminant analysis during the pilot test. The observed values should be compared to the pre-IAS concentrations to determine if a significant mass of contaminant is being pushed out of the groundwater. In general, it is difficult to assess the significance of this in a quantitative sense. However, if it is used in conjunction with the helium tracer data, the mass flux from the groundwater can be semi-quantified. To accomplish that, it can be assumed that the soil gas samples that have concentrations of helium near the injection concentration will reflect the contaminant concentrations being removed from the groundwater zone. When those concentrations are multiplied by the flow rate, a rough estimate of the mass removal rate can be obtained.

A more quantitative estimate of mass removal can be obtained if the IAS system is coupled with an SVE system. In this case, increases in contaminant concentrations in the off-gas, and the SVE extraction rate can be used to determine a mass removal rate. Of course, measurements made during the short duration of a pilot test are not indicative of long-term performance. However, it can generally be assumed that the pilot test data represent the maximum removal rate from the system. In that context, if mass removal rates during (e.g., at the conclusion) of the pilot test are too low, then there should be significant concern about the viability of IAS at the site.

3.6 Dissolved Oxygen Monitoring (PT6)

Dissolved oxygen data has the potential to identify the zone where oxygen is being delivered by the IAS system. If the preliminary measurements (PT1) showed low dissolved oxygen concentrations (e.g., less than 2 mg/L), it may be possible to identify areas where IAS has resulted in increases in DO. To determine this, dissolved oxygen should be measured in all groundwater monitoring points immediately following the pilot test. Unfortunately, several factors can complicate the interpretation of DO. First, at many sites where active biodegradation is ongoing, there may be significant quantities of reduced species (e.g., Fe(2+)) which act as rapid sinks for oxygen and which mask oxygen delivery to that region. Second, microbial activity may be high, effectively consuming oxygen as fast as it is delivered to the area. Finally, care must be taken to avoid artifacts caused by air entry into monitoring wells and preferential aeration within the well (Johnson et al., 1997). This is an important part of the reason why short-screened monitoring wells in the treatment zone were recommended for the pilot test.

3.7 Other Qualitative Observations

Often during pilot tests there are operational factors that are readily noticed and which are important to the viability of IAS. It is important to note any qualitative indicators of air distribution, such as bubbling or gurgling noises in wells, water "fountaining" out of monitoring points, etc. It is also important to be aware of odors due to the contaminants, noise due to the equipment, or other environmental factors. While these factors may not lessen the successful implementation of air sparging, they can make the system less feasible from a community impact perspective.

3.8 Site-Specific Design Approach

In cases where the Site-Specific Design Approach is being used, then it may be appropriate to conduct one or both of the tests described in the following sections.

3.8.1 SF_6 Distribution Test (PT7)

In this test, SF_6 is used as an analog for oxygen to determine the distribution of air in the groundwater zone (Johnson et al., 1996). SF_6 has a water solubility that is similar to oxygen; however, SF_6 has several advantages over oxygen and as a result the test can be both more sensitive and more quantitative. These advantages include: 1) it does not occur naturally, so background concentrations are essentially zero (unless it has been used at the site before); 2) SF_6 can be detected at extremely low concentrations in water and air, thus it is a much more sensitive tracer than oxygen; and 3) it is not biodegradable, so it acts as a conservative tracer to show where the air was delivered.

To conduct the test, SF_6 is blended with the injection air stream at a known concentration for a period of 12 to 24 h. The objectives in injecting for a short, known period are: 1) to provide an opportunity for SF_6 transfer from the air to the groundwater without a significant amount of groundwater transport; and 2) to allow an estimate of the mass transfer coefficient at various locations to be determined. The details of these procedures are discussed by Bruce and Johnson (2000). In overview, at the end of the SF_6 injection period, groundwater samples are collected and analyzed for SF_6. The duration of SF_6 injection and the cumulative volume of groundwater sample should recorded. Based on the concentration of SF_6 in the injected air, and the Henry's Law constant for SF_6, the percent saturation of SF_6 in the groundwater sample can be determined. In general, those concentrations can be divided into three groups. The first are values approaching saturation (e.g., >40% of theoretical solubility). These generally indicate that the sample location lies within the "zone of aeration" of the IAS system. The second group are samples contain low concentrations of SF_6 (e.g., <10%) and indicate that an air channel may be in the vicinity of the sampling location (e.g., it may be within the "zone of treatment"), but the air saturation in the aquifer at that point is probably low. The third group are samples which have no SF_6 present. These samples are presumed to lie outside both the aeration and treatment zones.

In the context of site-specific pilot tests, to be sufficiently conservative, the spacing of the IAS wells probably needs to be based on the size of the zone of aeration. Thus, for example, if high concentrations of SF_6 are observed at a distance of 15 ft, but not at 20 ft, then a well spacing of up to 30 ft might be appropriate, but greater than that would not be justified.

3.8.2 Geophysical Tests (PT8)

Users may also consider the use of geophysical tools for identification of the zone of aeration (and thus well spacing), although their use has not been prescribed in the Design Paradigm presented by Leeson et al. (2000). For example use of neutron probes, capacitance probes, and electrical resistance tomography are reported in the literature (e.g., Acomb et al. 1995; Lundegard and LaBreque 1998). These techniques generally have the ability to detect the presence of air in the subsurface at the "10% by volume" level. All of these techniques measure average properties over some roughly spherical volume. Depending on the specific technique, the diameters of those spheres over which air saturations are averaged range from 0.2 to 1 meter. Once again, it is important to remember that all of these techniques require background (i.e., pre-IAS) measurements.

4.0 INTERPRETATION OF PILOT TESTS: CASE HISTORY FROM EIELSON AFB, ALASKA

The tasks PT1 through PT6 outlined above, when taken together, allow the identification of major red flags to implementation of IAS. Furthermore, tasks PT7 and PT8 can provide the basis for decisions about well spacings larger than those in the Standard Design Approach. In the case history described below, the pilot test procedures discussed above are applied to determine if IAS is practical at a site at Eielson AFB, Alaska. The site is a large one in which IAS wells had initially been installed on 90-ft centers. As part of the ESTCP-sponsored Multi-site Air Sparging project, a "site-specific" pilot test was conducted at the site.

4.1 Site Description

The site is a jet fuel tank farm near the center of Eielson AFB. The aquifer at the site consists of 200 to 300 ft of loose alluvial sands and gravels overlying bedrock. The permeability of the aquifer is generally high and the water table is about 8 ft below ground surface. Soils overlying the aquifer are significantly finer-grained than the aquifer. Aquifer contamination consists of some "residual" jet fuel and dissolved contaminants in the upper few ft of the groundwater zone.

In preparation for the pilot test, a pair of IAS wells were installed adjacent to one another at the site. One well was screened about 6 ft below the water table and the other at about 10 ft below the water table in order to determine which depth was most effective for mass removal. The aquifer adjacent to the deeper well was thought to be somewhat finer-grained than near the water table. It is also important to note that the finer-grained soils extended to within a foot or two of the water table and limited the extent to which air could be removed from the subsurface by SVE. Four SVE wells were installed immediately around the IAS wells (Figure 2) and had screen lengths of 5 ft, which terminated at the water table. Twelve sampling nests consisting of a shallow piezometers and a deep vadose-zone monitoring point were installed around the site, with three wells at each of four distances (5,10, 15, and 20 ft). In addition, three fully-screened monitoring wells were installed at 10, 20, and 30 ft from the sparge wells for pressure measurements.

Air was delivered to the IAS system using a 5-horsepower (HP) oil-less compressor and steel piping. The SVE system was driven by two 3-HP regenerative blowers, although the flow capacity of the blowers could not be realized due to the low permeability of the soils.

4.2 Baseline Sampling (PT1)

Prior to initiation of the pilot test, water level measurements were made in the monitoring wells. Dissolved oxygen measurements made in the sampling points indicated that DO levels were below 2 mg/L. Prior to IAS startup, the SVE system was operated for several days to establish baseline contaminant concentrations, which were well below the 1 ppmv level for benzene, toluene, ethylbenzene, and total xylenes (BTEX). Monitoring of the SVE off-gas continued from that point through the remainder of the pilot test. Based on the baseline sampling, it was determined that the DO and off-gas data collected during a pilot test would be useful for assessing IAS performance.

Baseline pressure measurements also were collected in anticipation of conducting the groundwaer pressure response test as discussed in Section 4.4.

4.3 Injection Pressure/Flow Rate Test (PT2)

Prior to the IAS pilot test it was determined that flow rates of 5 to 20 ft^3/min would be used during the tests as recommended in Johnson et al. (2000). Initially air was injected at 5 ft^3/min into the shallow (6 ft below the water table) IAS well. The 5 ft^3/min flow rate was easily achieved and the injection pressure was essentially equal to the hydrostatic pressure. (Subsequent injection at 20 and 10 ft^3/min into the shallow and deep IAS wells, respectively, indicated that those flows could be easily achieved.)

4.4 Groundwater Pressure Response Test (PT3)

Subsequent to the initial shakedown of the IAS system, pressure transducers were placed in the three fully-screened monitoring wells and connected to a continuous data logger. Groundwater pressure responses were measured during startup and shutdown for 5 ft^3/min injection into the shallow well. These data are shown in Figure 3a. Pressure responses to IAS startup and shutdown for this test were very small (e.g., <0.01m). This indicates that in the vicinity of the IAS well screen, the formation was very permeable. When pressure was measured during startup and shutdown at 10 ft^3/min in the deep IAS well, the pressure changes were somewhat larger, indicating a somewhat lower permeability, but in general they were still small (e.g., <0.1m, Figure 3b). In general terms, the durations of the pressure changes were relatively short (although the fact that the pressure responses were so small complicates the interpretation of this somewhat). The picture resulting from this test is that air flows readily through the aquifer and the zone of aeration is established within a few minutes.

4.5 Helium Recovery Test (PT4)

Helium recovery tests were conducted in the shallow IAS well at 5 ft^3/min and in the deep IAS well at 10 ft^3/min. Because the maximum SVE extraction rate was only 15 ft^3/min, the recovery test conducted when the IAS injection rate was 20 ft^3/min will not be discussed here. The operating parameters for the test are shown in Table 2. Helium recovery for the two tests was very rapid and essentially 100% of the injected helium was recovered (Figure 4). These data indicate that, even though the SVE rate was quite low, the recovery was complete. This suggests that the zone of aeration was not very large and/or the majority of airflow in the vadose zone was confined to a narrow high-permeability zone in the vicinity of the water table. The question of size of the zone of influence will be addressed below both by the dissolved oxygen data and the SF_6 distribution test.

4.6 Off-Gas Sampling (PT5)

Because an SVE system was operating prior to and concurrently with the IAS system, SVE off-gas was used as a measure of contaminant mass flux resulting from sparging. Figure 5a shows hydrocarbon off-gas data during sparging at 5 ft^3/min into the shallow well. The concentrations are very low (~20 ppmv total) and the calculated mass removal is approximately 0.03 g/min. Mass removal at 20 ft^3/min in the shallow well gives similar results. These data once again suggest that the air sparged at this depth has a small zone of influence. When air was injected into the deep well at 10 ft^3/min, the concentrations were significantly higher, although still not terribly high (Figure 5b). In addition, the off-gas concentrations were sustained for a longer period of time than for the shallow well. Based on these data and other pilot test activities, it was concluded that the deeper well should be used for sparging.

4.7 Dissolved Oxygen Measurement (PT6)

At the conclusion of the pilot test groundwater samples were collected from the 12 sampling points. The data are shown in plan view in Figure 6. The data indicate that sampling points 1, 3, 4, 5, 7, 8, 10, and 12 had elevated levels of DO, suggesting that the air reached the treatment zone at a distance from the IAS well of from 10 to 20 ft. These data will be compared to the SF_6 data in PT7, below.

4.8 SF_6 Distribution Test (PT7)

Because the site is large, it was desirable to use a well spacing larger than the standard 15 ft value for full-scale installation. As a result, an SF_6 distribution test was conducted at the site. SF_6 was added to the sparge air of the deep well at a concentration of ~ 1,000,000 parts per trillion by volume (1 ppmv) for about approximately 16 hours. Subsequent to that, groundwater samples were collected from all of the sampling points. The data indicate that elevated levels of SF_6 were observed at points 1, 3, 4, 5, 7, 8, and 10 (Figure 7). This suggests that the zone of aeration extended between 10 and 15 ft away from the sparge well. Based on these data it would be concluded that the spacing of the IAS wells might be increased somewhat over the standard 15-ft spacing, but probably to a maximum value of 20 to 25 ft.

4.9 Summary

The conclusions of the pilot test data indicate that sparging in the deep (i.e., 10 ft below the water table) well might be an effective approach for remediating the site. The IAS air was easily injected and collected and mass was being removed. The SF_6 distribution test indicated that the zone of aeration was not large (10 to 15 ft from the IAS well), thus well spacings greater than 20 to 25 ft would not be recommended. This may limit the applicability of the technology at this large site. On the other hand, installation of IAS wells using direct push technology should be possible at the site, and it may not be necessary to use the SVE system, due to the isolated location of the site. In addition, it may be acceptable to place all of the IAS piping above ground surface. Given these factors, it may be practical to install a large number of sparging points, and/or to progressively sweep a sparging system across the site (Leeson et al., 2000, this issue).

5.0 REFERENCES

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Table 1. Summary of Pilot Test Activities

	Activity	Question(s) Answered	Standard Pilot Test Approach	Site-Specific Pilot Test Approach
PT1	Baseline sampling • DO • Pressure • Soil gas • Geophysical[1]	What are aquifer conditions prior to IAS startup?	X	X
PT2	Injection pressure/ flow rate test	Is it possible to achieve desired flow rate at reasonable pressures?	X	X
PT3	Groundwater pressure response test	What are the general characteristics of the air distribution - is it likely to be more like the semi-conical homogeneous-setting air distribution or is there a significant degree of stratification?	X	X
PT4	Helium tracer test	What is the approximation of lateral extent of the air distribution? Are there indications of preferred directions?	X	X
PT5	Soil gas/off-gas sampling	What is the volatilization rate? Are there any obvious safety hazards?	X	X
PT6	Dissolved oxygen measurements	What is the approximation of lateral extent of the air distribution? Are there indications of preferred directions?	X	X
PT7	Sf_6 distribution test	What is the vertical and lateral extent of the air distribution in the target treatment zone? What are the oxygen transfer rates to groundwater?		X
PT8	Other geophysical tools	What is the vertical and lateral extent of the air distribution in the target treatment zone?		Optional

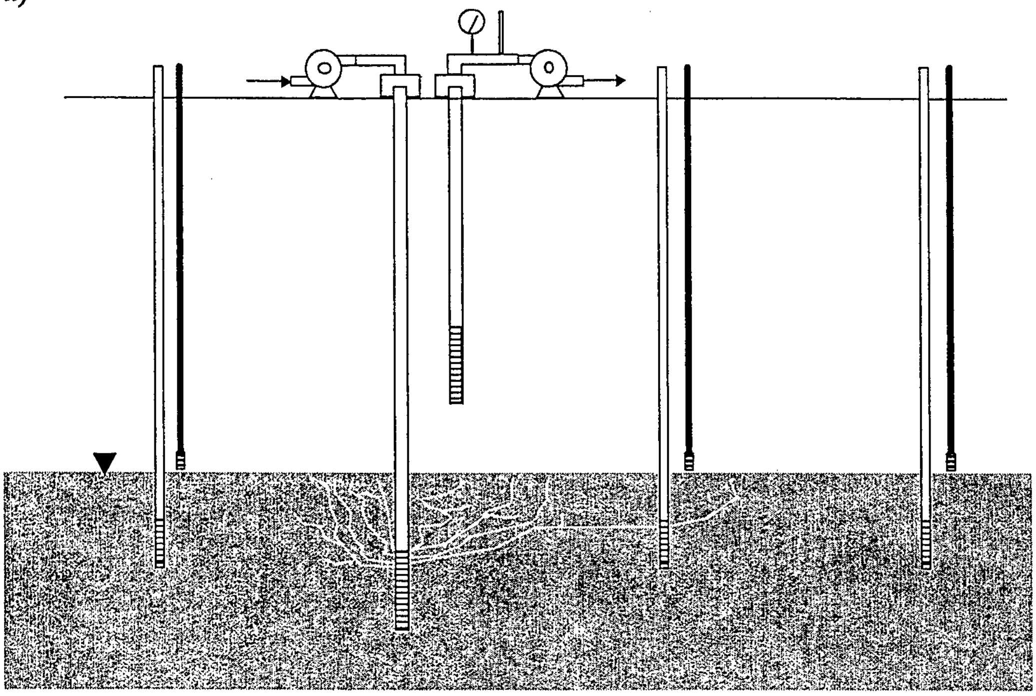
[1]Collect initial geophysical measurements if PT8 will be conducted.

Table 2. Operating Conditions for the Helium Recovery Tests

Parameter	Test		
	Shallow: 5 ft^3/min	**Shallow: 20 ft^3/min**	**Deep: 10 ft^3/min**
Approximate injection rate (ft^3/min)	5	20	10
Approximate extraction rate (ft^3/min)	15	15	15
Helium injection rate (LPM)	7	15	15
Injection concentration (%)	6.6	3.3	6.4
Calculated injection rate (ft^3/min)	4.3	16	9.9
100% extraction concentration (%)	2.3	3.6	3.6
Calculated extraction rate (ft^3/min)	12	15	14.8

Figure 1. Plan and cross-section views of a sample pilot test layout

a)



b)

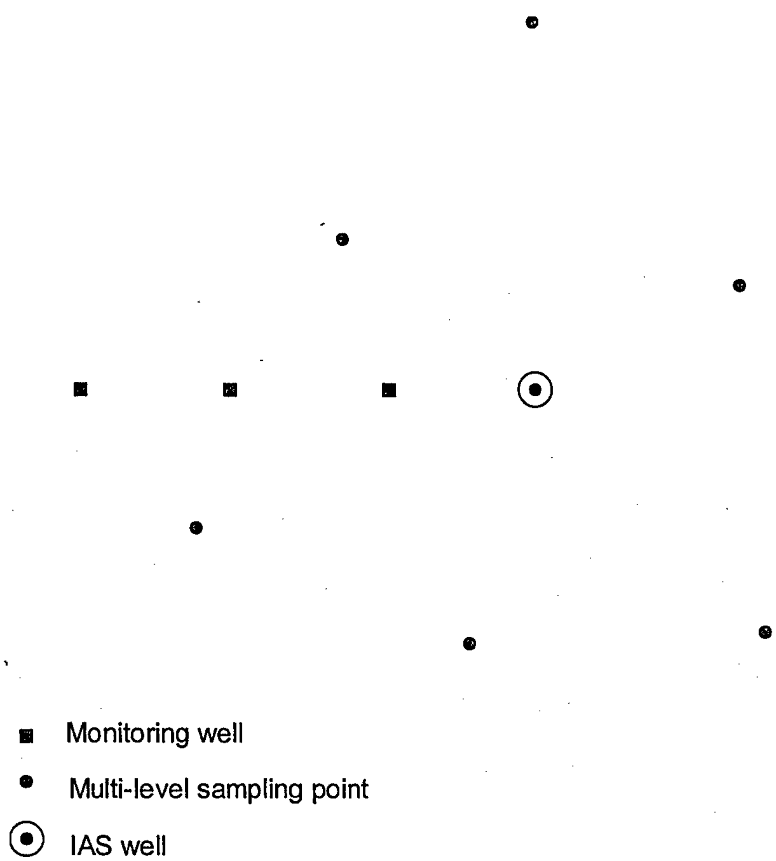


Figure 2. Plan view layout for the Eielson AFB pilot test.

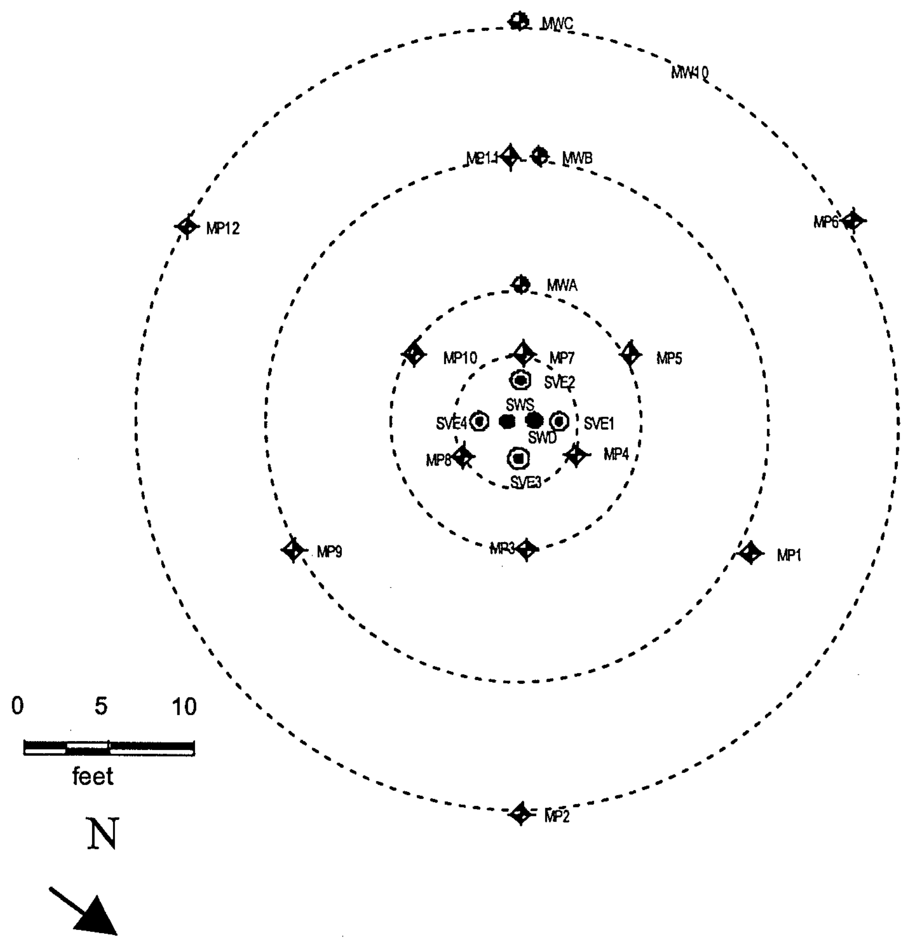


Figure 3. Groundwater pressure data from the: a) shallow IAS well at 5 ft^3/min; and b)deep IAS well at 10 ft^3/min.

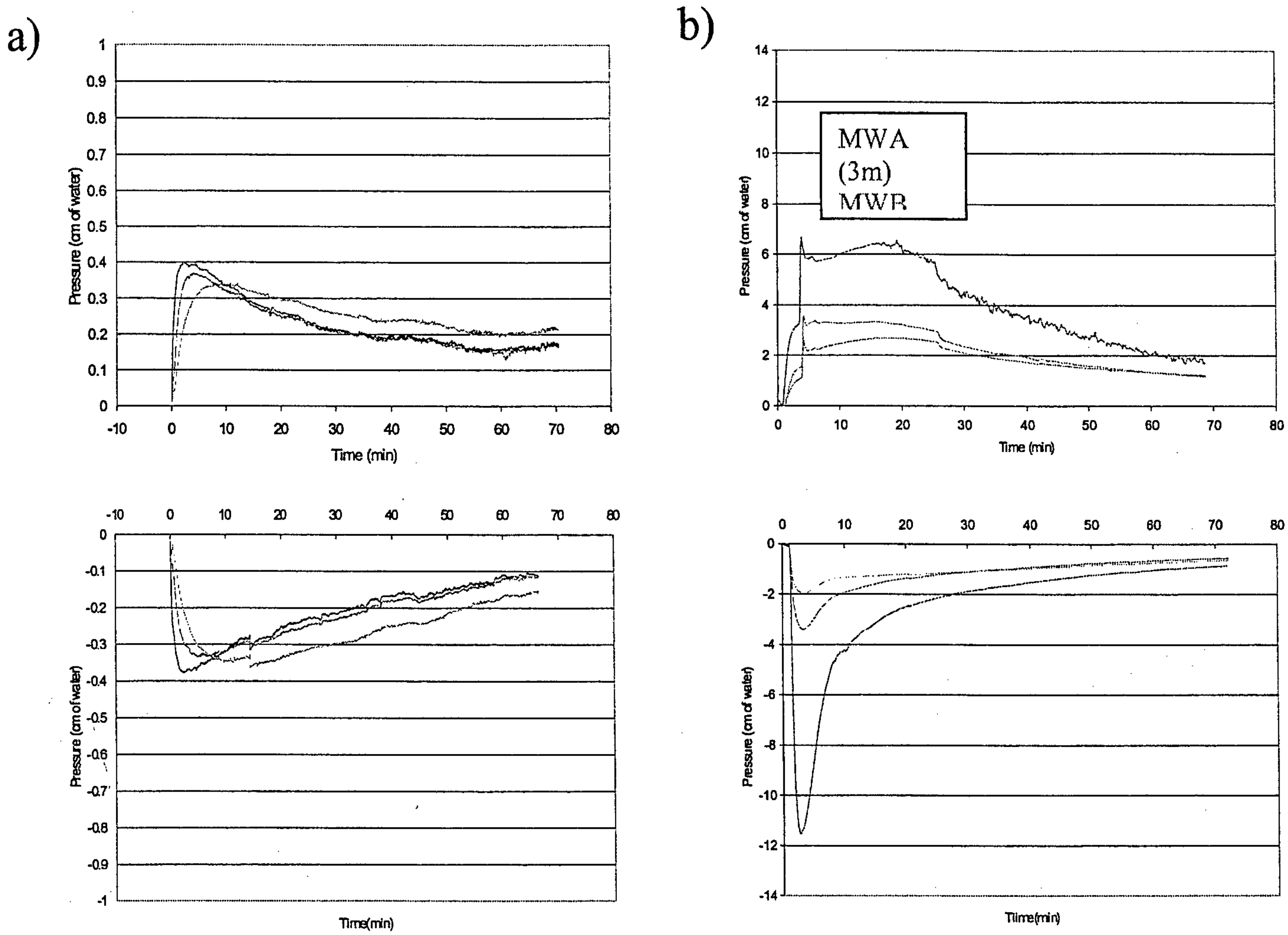
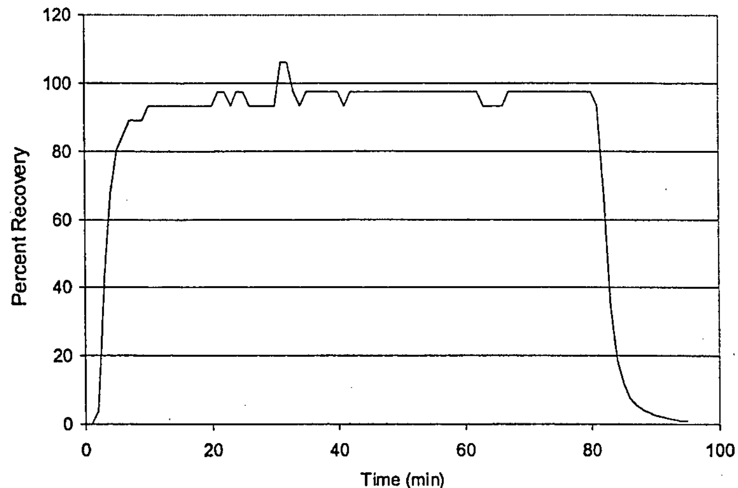


Figure 4. Helium recovery test data for the: a) shallow IAS well at 5 ft^3/min; and 2) deep IAS well at 10 ft^3/min.

a)



b)

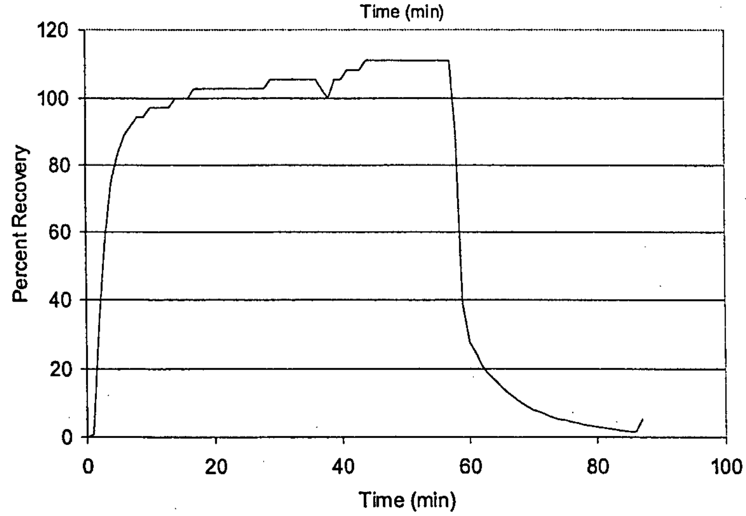
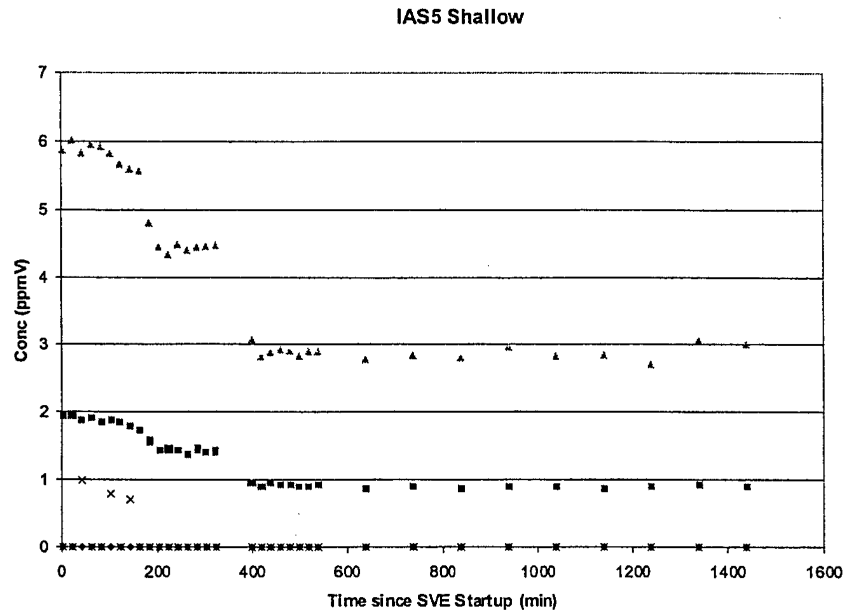


Figure 5. Hydrocarbon off-gas data (ppmv) during the: a) shallow IAS well at 5 ft^3/min; and 2) deep IAS well at 10 ft^3/min.



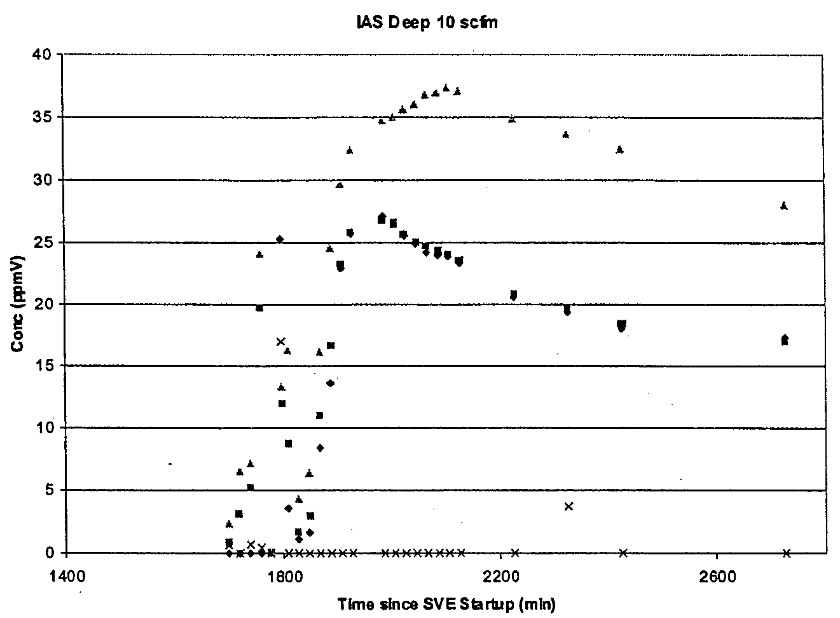


Figure 6. Eielson AFB plan view site map showing dissolved oxygen data taken at the conclusion of the IAS pilot test.

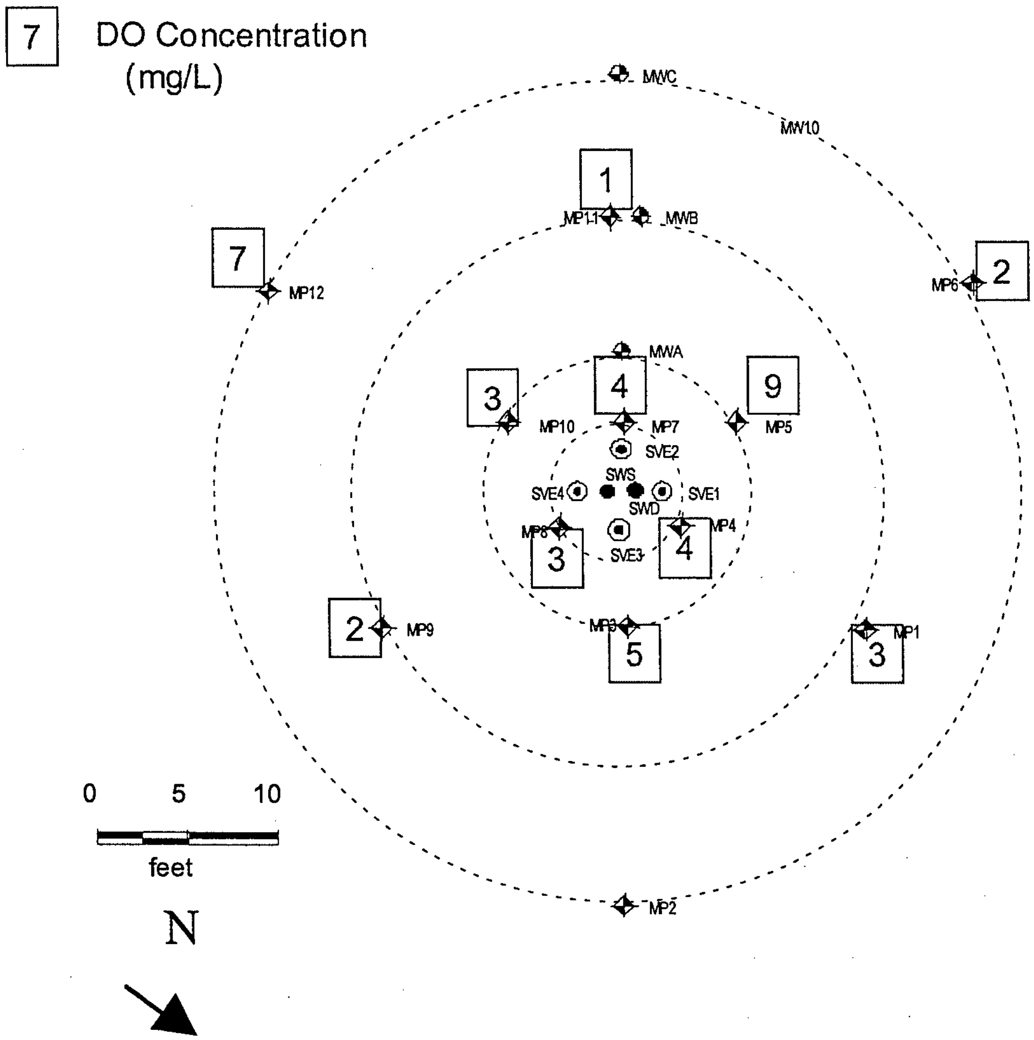


Figure 7. Eielson AFB plan view site map showing SF_6 data (reported as percent saturation with respect to the concentration of SF_6 in the injection air).